

Comparison of Calculated Dose by Helical Tomotherapy Treatment Planning Machine and Measured Dose of Radiophotoluminescence Glass Dosimeter in Lung Lesions Using Rando Phantom

HIDEYA YAMAZAKI^{1,2}, KAZUKI IWAMA², TAKUYA NISHIMURA^{1,2}, YASUNORI IWAI³, NORIHIRO AIBE^{1,2}, TADASHI TAKENAKA³, SHUNSUKE MIYAKE³, EIICHI TANAKA³, KEN YOSHIDA³, YOSHITAKA OOTA², HIROYASU IKENO¹, SATOAKAI NAKAMURA¹ and HARUUMI OKABE²

¹Department of Radiology, Graduate School of Medical Science, Kyoto Prefectural University of Medicine, Kamigyo-ku, Kyoto, Japan;

²Department of Radiology, Ujitakeda Hospital, Uji City, Kyoto, Japan;

³Department of Radiology, National Hospital Organization, Osaka National Hospital, Osaka City, Osaka, Japan

Abstract. Aim: To examine the compatibility of the measured and calculated dose for the treatment of lung lesions by helical tomotherapy. Materials and Methods: The administered dose was measured a total of 55 times at 22 points with a radiophotoluminescence glass dosimeter (RPLGD) inserted in the position of an anthropomorphic Rando Phantom. Two Gy were prescribed and calculated with a tomotherapy planning machine for a 3-cm diameter spherical planning target volume (PTV) created in the lung area. Compatibility (measured dose/calculated dose and σ value= $(D_{meas}-D_{calc})/D_{prescribed} \times 100$ (%)) was analyzed according to dosimeter location. Results: Deviations between measured and calculated doses for the lung lesion were within 4% for planning target volume, indicating that adequate dose delivery to the PTV was achievable. On the other hand, we found dose deviations up to 15% for the lower prescribed dose range (64% or less) for the measured dose/calculated comparison and a 6% deviation according to the σ value in or near inhomogeneous tissue. Conclusion: Although the measured dose satisfied the clinical requirement in almost all areas including PTV, we should note that there may be discrepancies between expected calculated dose and irradiated dose in or near inhomogeneous area.

Correspondence to: Hideya Yamazaki, MD, Department of Radiology, Kyoto Prefectural University of Medicine, 465 Kajicho Kawaramachi Hirokoji, Kamigyo-ku, Kyoto, Kyoto 602-8566 Japan. E-mail: hideya10@hotmail.com

Key Words: Tomotherapy, lung tumor, stereotactic body radiotherapy, radiophotoluminescence glass dosimeter, Rando phantom.

Stereotactic body radiotherapy (SBRT) is a method for increasing the radiotherapy dose delivered to the tumor while minimizing that offered to surrounding normal tissue. This technique has been well-described in the literature, and clinical trials suggest promising results (1-3). These findings prompted us to initiate SBRT using helical tomotherapy (HT), which is a technology that delivers fan-beam intensity modulated radiation therapy (IMRT) under megavoltage computed tomography (MVCT) guidance through continuous and synchronous gantry rotation and couch movement during radiation delivery, which facilitates daily image-guided radiation therapy (IGRT) administration. There is limited information on the clinical use of HT in lung cancer. In spite of the advantages of high setup accuracy, adaptive RT-planning capability, and sparing of normal tissues, low-dose shower is of concern in HT, where radiation is given over 360 degrees (4-6). Side-effects by low-dose shower may be enhanced by additional chemotherapeutic agents. Shueng *et al.* reported severe radiation pneumonia after 30 Gy/10 fractions of HT radiotherapy and subsequent chemotherapy for T8-T10 metastasis for symptom relief (4). Song *et al.* reported that HT has produced a somewhat high rate of fatal pulmonary complications. They suggest that the percentage volume of lung irradiated by more than 5 Gy; V5 should be considered and kept as low as possible in addition to the conventional dosimetric factors (5). SBRT using a linear accelerator was found to produce a rather homogeneous dose distribution in planning target volume, but IMRT showed dose inhomogeneity with a steep dose gradient which may lead to inadequate target coverage or a higher dose to wider surrounding normal tissue, and caution should be taken especially when a new chemotherapeutic agent is used (3,6). Hsieh *et al.* advised caution for combination SBRT using HT

and erlotinib regarding the potential risks of enhanced adverse effects (6).

SBRT using HT is performed in several institutes including ours, using custom-made phantom as an accompanying quality assurance item for HT. As there is much ambiguity still within the quality assurance system, we independently attempted to confirm the reliability of dose delivery for consistency of lung tumor SBRT using HT. We selected a 3-D anthropomorphic phantom (Rando phantom) equipped with a radiophotoluminescence glass dosimeter (RPLGD) because of its similarity to the real clinical conditions. The Rando phantom is a widely-available anthropomorphic phantom that has been used for many years for dose measurements in a variety of applications (7-9). The RPLGD was developed in the 1950s and has subsequently been used for radiotherapeutic dosimetry because of its several superior features (10-13). RPLGDs possess good properties for *in vivo* dosimetry, including small size, ruggedness, nontoxicity, photon-energy and dose rate independence over the energy range 0.2-0.3 MeV, high sensitivity, good reproducibility, and repeat readability until the detectors become annealed. Linearity and reproducibility were better than for previous thermoluminescent dosimeters (TLD)(14-16). These advantages have made RPLGDs more robust than TLDs for *in vitro* dosimetry. We, therefore, used RPLGDs to establish quality assurance systems for brachytherapy and found deviation between the calculated and measured dose of 10% or more (10,11). Although RPLGDs have less accuracy than an ionization chamber, it enables us to examine the dose to a smaller volume, which is also suitable for IMRT because of its steep dose gradient. For these reasons, we used Rando phantom and RPLGD for quality assurance analysis of HT SBRT.

Materials and Methods

The element of the RPLGD (Dose Ace; Chiyoda Technol Corporation, Tokyo, Japan) is 1.5 mm in diameter and 8.5 mm in length, and the holder is 2.8 mm diameter and 9.5 mm length. A reader (FGD-1000, Chiyoda Technol, Tokyo, Japan) stimulates the RPLGD using a pulsed ultraviolet laser, and readout range is 10 μ Gy to 10 Gy. The linear dose response for 1 to 136 Gy for the RPLGD has been confirmed (17). RPLGDs are made of uniform glass with an effective atomic number of 12.039, containing 11.00% Na, 31.55% P, 51.16% O, 6.12% Al, and 0.17% Ag by weight. RPLGDs with their holders were inserted into an adult female Rando phantom (The Phantom Laboratory, Salem, NY, USA) (Figure 1).

Each cross section of Rando phantom has a 2.5 cm thickness, and each slice of phantom material contained a grid of plugs that could be removed to allow the insertion of RPLGDs with holders. We obtained measurements at 18 points in the central plane including four points on the body surface (Figure 2).

We also examined two cross sections in both upper and lower directions, at a point corresponding to the central position of the PTV in the central plane. We measured the point dose three times in

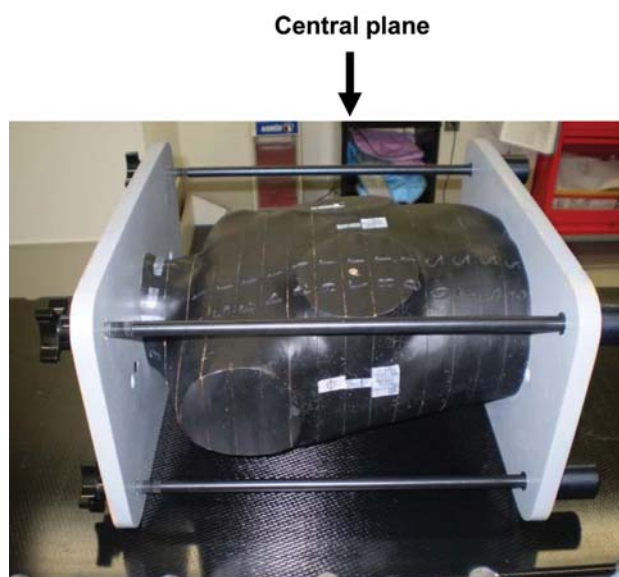


Figure 1. Adult female Rando phantom.

general, except for the distant area (13, 14, 15, 16, 17, 18, 17) from PTV, for the limitation of entire number of RPLGDs. CT images with a 3-mm slice thickness were acquired with an Aquilion 64 (Toshiba Medical Co., Tokyo, Japan). The images were transferred to a treatment planning system (TPS) radiotherapy plan (Tomotherapy Planning Station Version 3.1.5.3 Hi-Art system; TomoTherapy Incorporated, Madison, WI, USA). The gross tumor volume (GTV) was rendered as a sphere 20 mm in diameter and the PTV (27.79 cm³) was automatically generated by the addition of a 5 mm margin to GTV. For SBRT, we used the prescribed dose of 50 Gy in five fractions for D95. Organs at risk were delineated in lung, spinal cord, and trachea. Dose constraints for the prescription dose of 50 Gy delivered in five fractions were a maximum tolerated dose of 28 Gy for the spinal cord, 44 Gy for the esophagus (we could not use this constraint because the Rando phantom does not include an esophageal structure), and lung V20 <20% mean lung dose <10 Gy. The total lung volume equaled that of both lungs minus that of the GTV, while V20 is the percentage of the lung volume receiving 20 Gy or more. For this mock RT plan, we divided 10 Gy into a five-fraction plan by dividing all values by 5 (Figure 3), and for this investigation, the prescribed dose was set at a single fraction of 2 Gy.

All these parameters were found to be adequate (maximum dose for the spinal cord was 0.452 Gy, V20=15%, mean lung dose=0.95 Gy). The maximum dose for PTV was 10.37 Gy and the minimum dose was 9.63 Gy. The superposition, convolution algorithm was adopted for dose calculations. Irradiation was performed with a Hi-Art Helical Tomotherapy system (Accuray Co. Sunnyvale, CA USA). Following irradiation, RPLGDs were removed from the phantom for estimation. Doses were measured for the one or three administrations, depending on the location, and the average value was regarded as the calculated dose for the given RPLGD. Calibration of RPLGDs and linearity was confirmed by methods described elsewhere (10, 11). Individual correction factors were then generated for each RPLGD. The procedures were repeated five times.

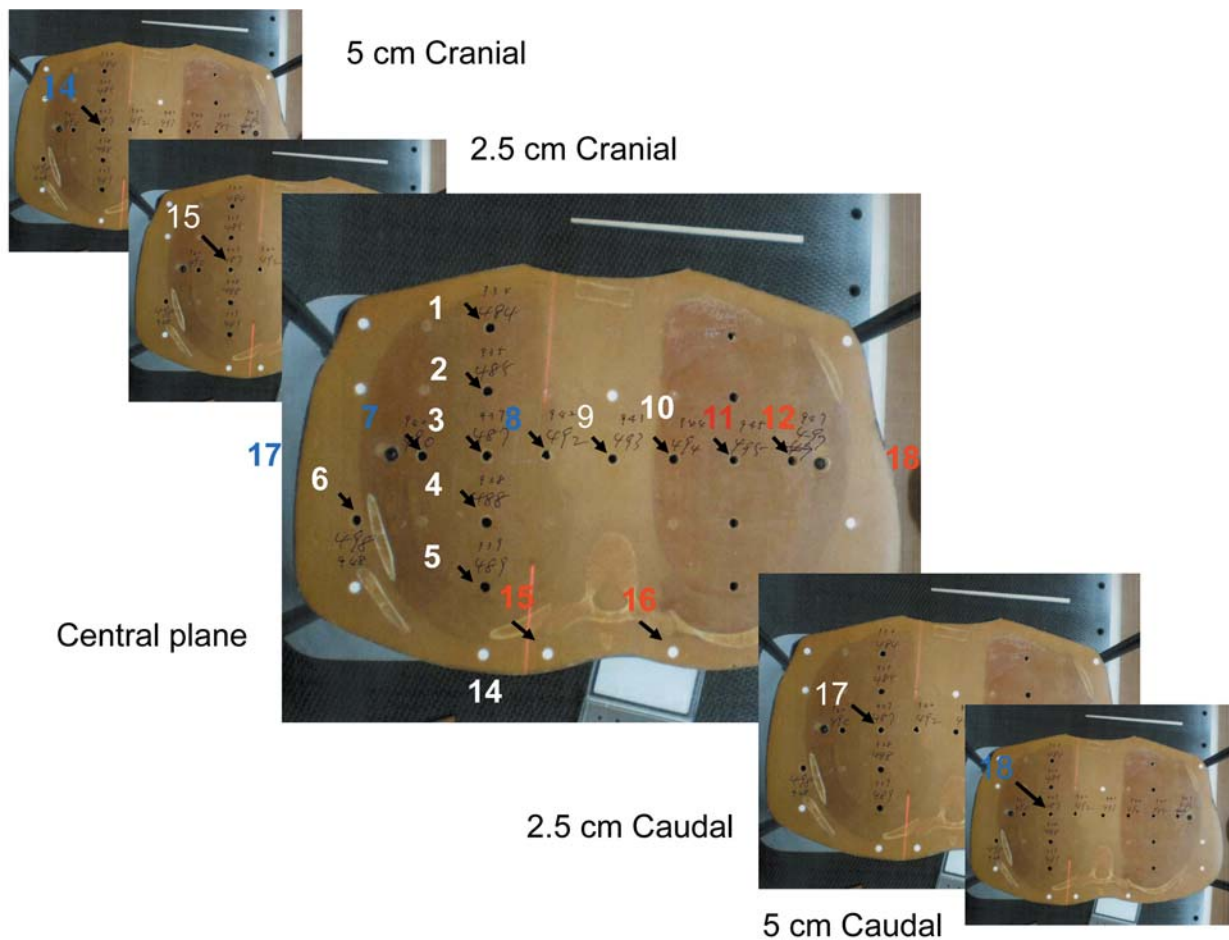


Figure 2. Calculated positions and comparison of calculated dose by helical tomotherapy treatment planning machine and measured dose of radiophotoluminescence glass dosimeter (RPLGD) in a lung lesion using a Rando phantom. These photographs were taken from a cranial direction (mock tumor was located in the left lung). Higher dose, 105% of calculated, shown in red; acceptable dose ratio 95-105%, shown in white; lower dose, less than 95% of calculated shown in blue.

Absorbed dose from MVCT. The absorbed dose from MVCT was assessed by using RPLGDs in similar positions (1, 3, 5, 11, 14, 15, 16, 17, 18) which were then exposed to 3 MV X-rays.

Results

Results for RPLGDs. The absorbed doses measured by RPLGDs after irradiation of the female Rando phantom are presented in Table I. Deviations between measured and calculated doses for the lung lesion were determined as a ratio. The calculation grid size is 3.8 mm. Table II and Figure 2 show differences of more than 5% between the calculated and estimated dose. We also calculated $\sigma = (D_{\text{meas}} - D_{\text{calc}}) / D_{\text{prescribed}} \times 100$ (%) for reference (Tables I and II).

We found that deviations were within 5% of the PTV, which demonstrates that an adequate dose delivery to the

PTV is feasible. Although we found dose deviations of up to 15% for the lower prescribed dose range (64% or less) and/or the inhomogeneous area adjacent to bone (Figure 4), only one point (7; 3 cm to the right of the PTV center, ipsilateral lung) had 6% deviation according to the σ value. Interestingly, good concordance was found in locations in vertical positions and deviations of more than 5% were detected only in the horizontal direction of PTV (Figure 2).

Absorbed dose from MVCT. The PTV area (3 cm in length) was subjected to MVCT. The slice thickness is 4 mm in MVCT. The following doses were absorbed from MVCT: 1, 1.6 cGy; 3, 1.6 cGy; 5, 1.6 cGy; 11, 1.7 cGy; 14, 0.1 cGy; 15, 0.3 cGy; 16, 1.6cGy; 17, 0.8 cGy; 18, 0.1 cGy. The central plane received 1.6-1.7 cGy, the adjacent plane 0.3-0.8 cGy and the 5 cm caudal or cranial plane 0.1 cGy.

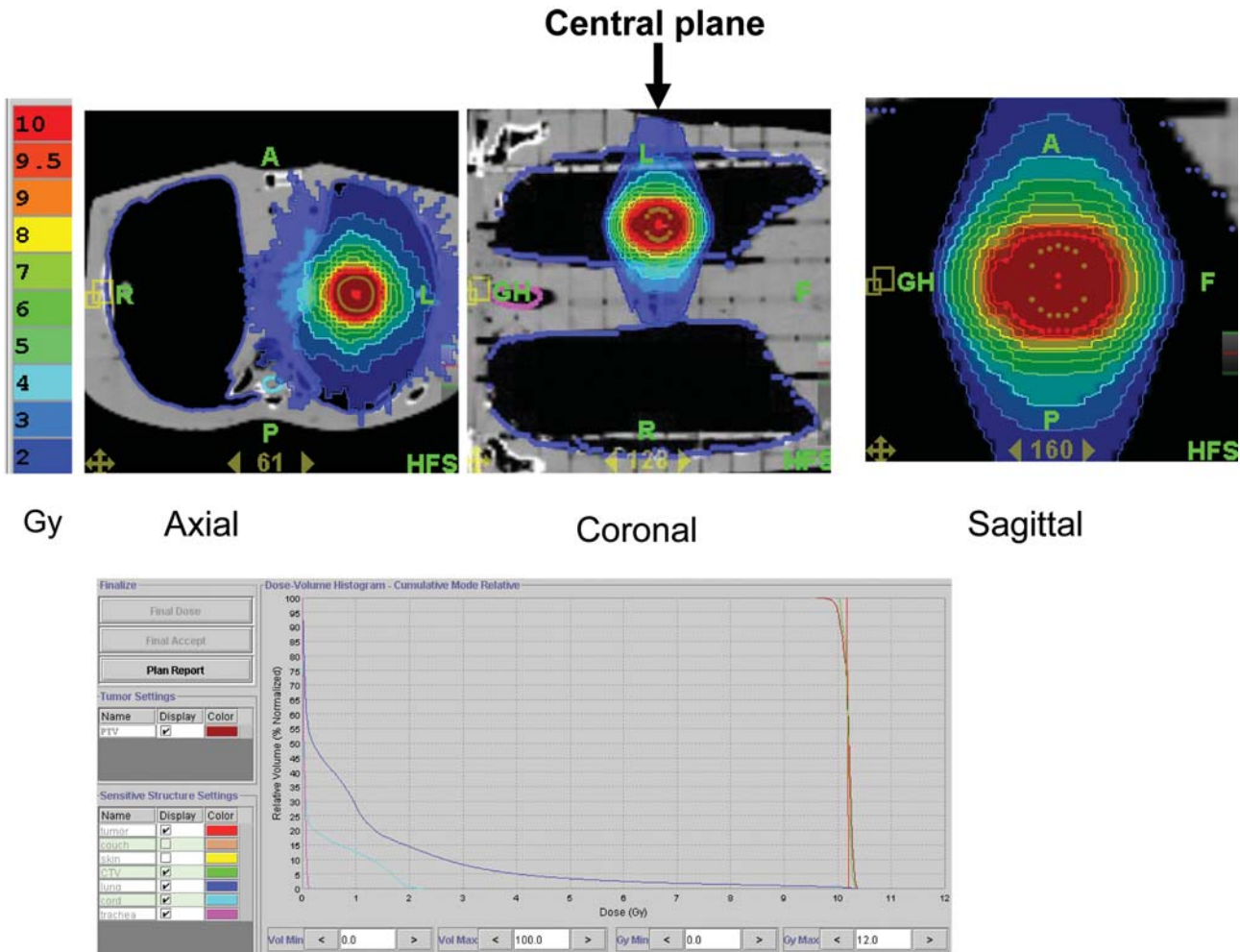


Figure 3. Stereotactic body radiotherapy plan generated by treatment planning system for mock lung tumor. The prescribed dose is 10 Gy in five fractions.

Discussion

Helical tomotherapy is a relatively new tool capable of SBRT with both advantages and disadvantages compared to other treatment systems. Firstly, as a CT-based technology with greatly expanded degrees of freedom, it allows for excellent dose sculpting, and provides outstanding conformity of the prescribed dose to the target. The megavoltage CT scan performed immediately before treatment potentially allows for smaller PTV expansions due to reduced setup uncertainty, thereby permitting acceptance of a higher treatment dose (18). On the other hand, tomotherapy currently allows only for coplanar treatment, which results in less capability than that of non-coplanar treatment methods for spreading the exit and entrance dose outside the radial plane. An additional concern is tumor motion, which may theoretically cause tumor underdosing. However, several previous investigations

have shown that such concerns are somewhat unrealistic and not likely to have any significant dosimetric consequences (19, 20). Consequently, SBRT using tomotherapy is considered acceptable for clinical usage (21, 22) and this prompted us to initiate lung SBRT using tomotherapy.

The Rando phantom is a widely available anthropomorphic phantom that has been used for many years for dose measurements in a variety of applications (7-9). Measuring the dose at any given point in the Rando phantom is straightforward, and it has been used in diagnostic radiology, radiotherapy, and radiation protection (23, 24). In principle, the Rando phantom should enable investigators to perform an objective comparison of the radiation doses received by normal-sized adults in a wide range of settings. In the present study, we used a newly-developed RPLGD, which is characterized by easier handling and high reliability (14-16). Dispersion of response among dosimeters is small (coefficient

Table I. Radiophotoluminescence glass dosimeter dose-verification results.

Location	Examined dose			Average (cGy)	Calculated dose (cGy)	Prescribed dose (%)	Ratio average/calculated	σ
	1st exam	2nd exam (cGy)	3rd exam					
1	56.0	56.4	57.8	56.7	56.8	28%	100%	0.0%
2	120.9	122.2	121.4	121.5	123.4	61%	98%	1.0%
3	195.5	194.9	196.4	195.6	203.6	100%	96%	4.0%
4	105.7	104.9	NA	105.3	109.6	54%	96%	2.2%
5	54.6	53.7	56.7	55.0	54.4	27%	101%	0.3%
6	50.1	49.3	49.8	49.7	48.6	24%	102%	0.6%
7	120.3	114.1	116.5	117.0	129.4	64%	90%	6.2%
8	116.8	118.3	123.9	119.7	127.4	63%	94%	3.9%
9	52.4	51.8	53.5	52.6	52.2	26%	101%	0.2%
10	33.9	34.7	35.2	34.6	34.8	17%	99%	0.1%
11	29.8	29.9	30.8	30.2	27.6	14%	109%	1.3%
12	23.4	22.9	24.3	23.5	21.6	11%	109%	1.0%
13	29.8	NA	NA	29.8	28.8	14%	104%	0.5%
14	30.3	NA	NA	30.3	30	15%	101%	0.1%
15	35.2	NA	NA	35.2	33.4	16%	106%	0.9%
16	23.7	NA	NA	23.7	21.8	11%	109%	0.9%
17	30.4	NA	NA	30.4	34.8	17%	87%	2.2%
18	12.7	NA	NA	12.7	11.2	6%	114%	0.8%
18	14.8	14.8	15.1	14.9	16	8%	93%	0.6%
17	180.2	184.7	NA	182.5	176.8	87%	97%	2.8%
15	172.7	172.5	175.0	173.4	172.7	85%	100%	0.4%
14	6.9	6.9	6.8	6.9	7.9	4%	87%	0.5%

NA, Not available; 3, PTV center; $\sigma=(D_{\text{meas}}-D_{\text{calc}})/D_{\text{prescribed}} \times 100(\%)$ according to the formula of Ezzell *et al.* (26).

Table II. Differences of more than 5% between calculated and estimated dose.

Location	% Prescribed dose (%)	Ratio*	σ	Anatomy
14	4%	87%	0.5%	Ipsilateral lung, 5 cm cranial plane
17	17%	87%	2.2%	Lateral skin surface, ipsilateral side
7	64%	90%	6.2%	3 cm Right of PTV center, ipsilateral lung
18	8%	93%	0.6%	Ipsilateral lung, 5 cm caudal plane
8	63%	94%	3.9%	3 cm Left, border area (lung and mediastinum)
15	16%	106%	0.9%	10 cm From PTV center, adjacent to bone
16	11%	109%	0.9%	12 cm From PTV center, adjacent to bone
12	11%	109%	1.0%	16 cm Left of PTV center, contralateral lung
11	14%	109%	1.3%	12 cm Left of PTV center, contralateral lung
18	6%	114%	0.8%	Lateral skin surface, contralateral side

*Odd average measured dose to calculated dose. $\sigma=(D_{\text{meas}}-D_{\text{calc}})/D_{\text{prescribed}} \times 100(\%)$.

of variation 0.82%), and reproducibility of repeat measurements by a single element is excellent (coefficient of variation 0.29%), and better than commercially available TLDs (8). The largest source of error in calculations exist in tissue inhomogeneities, such as the case found in the lung or bony anatomy and the resultant loss of electronic equilibrium. It is reported that the presence of large heterogeneities cannot be entirely accounted for by the superposition-convolution

algorithm when compared to dosimetric measurements, especially in lower-dose areas (25). We found a borderline 6% deviation according to the σ value at 3 cm to the right of the PTV center in the ipsilateral lung, the clinical significance of this deviation is not clear and requires further investigation.

In conclusion, although the measured doses satisfied the clinical requirement in almost all areas including PTV, it should be borne in mind that there may be discrepancies

between the expected calculated dose and the irradiated dose in inhomogeneous areas.

References

- Onishi H, Araki T, Shirato H, Nagata Y, Hiraoka M, Gomi K, Yamashita T, Niibe Y, Karasawa K, Hayakawa K, Takai Y, Kimura T, Hirokawa Y, Takeda A, Ouchi A, Hareyama M, Kokubo M, Hara R, Itami J and Yamada K: Stereotactic hypofractionated high-dose irradiation for stage I non-small cell lung carcinoma: Clinical outcomes in 245 subjects in a Japanese multiinstitutional study. *Cancer 101*: 1623-1631, 2004.
- Nagata Y, Wulf J, Lax I, Timmerman R, Zimmermann F, Stojkovski I and Jeremic B: Stereotactic radiotherapy of primary lung cancer and other targets: results of consultant meeting of the International Atomic Energy Agency. *Int J Radiat Oncol Biol Phys 79*: 660-669, 2011.
- Baisden JM, Romney DA, Reish AG, Cai J, Sheng K, Jones DR, Benedict SH, Read PW and Lerner JM: Dose as a function of lung volume and planned treatment volume in helical tomotherapy intensity-modulated radiation therapy-based stereotactic body radiation therapy for small lung tumors. *Int J Radiat Oncol Biol Phys 68*: 1229-1237, 2007.
- Shueng PW, Lin SC, Chang HT, Chong NS, Chen YJ, Wang LY, Hsieh YP and Hsieh CH: Toxicity risk of non-target organs at risk receiving low-dose radiation: Case report. *Radiat Oncol 4*: 71, 2009.
- Song CH, Pyo H, Moon SH, Kim TH, Kim DW and Cho KH: Treatment-related pneumonitis and acute esophagitis in non-small-cell lung cancer patients treated with chemotherapy and helical tomotherapy. *Int J Radiat Oncol Biol Phys 78*: 651-658, 2010.
- Hsieh CH, Chang HT, Lin SC, Chen YJ, Wang LY, Hsieh YP, Chen CA, Chong NS, Lin SL, Chen CY and Shueng PW: Toxic risk of stereotactic body radiotherapy and concurrent helical tomotherapy followed by erlotinib for non-small-cell lung cancer treatment-case report. *BMC Cancer 10*: 696, 2010.
- Wyatt M, Corredor C, Tamimi M and Miller LF: Comparison of treatment planning dose calculations with measurements and Monte Carlo calculations in a RANDO phantom. *Radiat Prot Dosimetry 2005, 116*: 461-465, 2005.
- Alderson SW, Lanzi LH, Rollins M and Spira J: An instrumented phantom system for analog computation of treatment plans. *Am J Roentgenol 87*: 185-195, 1962.
- Scalzetti EM, Huda W, Bhatt S and Ogden KM: A method to obtain mean organ doses in a RANDO phantom. *Health Phys 95*: 241-244, 2008.
- Nose T, Koizumi M, Yoshida K, Nishiyama K, Sasaki J, Ohnishi T, Kozuka T, Gomi K, Oguchi M, Sumida I, Takahashi Y, Ito A and Yamashita T: *In vivo* dosimetry of high-dose-rate brachytherapy: Study on 61 head-and-neck cancer patients using radiophotoluminescence glass dosimeter. *Int J Radiat Oncol Biol Phys 61*: 945-953, 2005.
- Nose T, Koizumi M, Yoshida K, Nishiyama K, Sasaki J, Ohnishi T, Kozuka T, Gomi K, Oguchi M, Sumida I, Takahashi Y, Ito A and Yamashita T: *In vivo* dosimetry of high-dose-rate interstitial brachytherapy in the pelvic region: Use of a radiophotoluminescence glass dosimeter for measurement of 1004 points in 66 patients with pelvic malignancy. *Int J Radiat Oncol Biol Phys 70*: 626-633, 2008.
- Tsuda M: A few remarks on photoluminescence dosimetry with high energy X-rays. *Jpn J Med Phys 20*: 131-139, 2000.
- Araki F, Ikegami T, Ishidoya T and Kubo HD: Measurements of Gamma-Knife helmet output factors using a radiophotoluminescent glass rod dosimeter and a diode detector. *Med Phys 30*: 1976-1981, 2003.
- Hamers HP, Johansson KA, Venselaar JL, de Brouwer P, Hansson U and Moudi C: *In vivo* dosimetry with TLD in conservative treatment of breast cancer patients treated with the EORTC protocol 22881. *Acta Oncol 32*: 435-443, 1993.
- Anagnostopoulos G, Baltas D, Geretschlaeger A, Martin T, Papagiannis P, Tselis N and Zamboglou N: *In vivo* thermoluminescence dosimetry dose verification of transperineal ¹⁹²Ir high-dose-rate brachytherapy using CT-based planning for the treatment of prostate cancer. *Int J Radiat Oncol Biol Phys 57*: 1183-1191, 2003.
- International Commission on Radiation Units and Measurements (1997). Dose and Volume Specification for Reporting Interstitial Therapy (ICRU report 58). ICRU, Washington DC, 1998.
- Perry JA: Instrumentation and technique. In: RPL Dosimetry. Radiophotoluminescence in Health Physics. Perry JA ed., IOP, Bristol, UK, pp.141-160, 1987.
- Kanagaki B, Read PW, Molloy JA, Lerner JM and Sheng K: A motion phantom study on helical tomotherapy: The dosimetric impacts of delivery technique and motion. *Phys Med Biol 52*: 243-255, 2007.
- Kissick MW, Mo X, McCall KC, Schubert LK, Westerly DC and Mackie TR: A phantom model demonstration of tomotherapy dose painting delivery, including managed respiratory motion without motion management. *Phys Med Biol 55*: 2983-2995, 2010.
- Tomita N, Kodaira T, Matsuo M, Furutani K, Tachibana H, Daimon T and Shimizu H: Helical tomotherapy for solitary lung tumor: Feasibility study and dosimetric evaluation of treatment plans. *Technol Cancer Res Treat 9*: 407-415, 2006.
- Fuss M, Shi C and Papanikolaou N: Tomotherapeutic stereotactic body radiation therapy: Techniques and comparison between modalities. *Acta Oncol 45*: 953-960, 2006.
- Hodge W, Tomé WA, Jaradat HA, Orton NP, Khuntia D, Traynor A, Weigel T and Mehta MP: Feasibility report of image-guided stereotactic body radiotherapy (IG-SBRT) with tomotherapy for early stage medically inoperable lung cancer using extreme hypofractionation. *Acta Oncol 45*: 890-896, 2006.
- Iwai K, Hashimoto K, Nishizawa K, Sawada K and Honda K: Evaluation of effective dose from a RANDO phantom in videofluorography diagnostic procedures for diagnosing dysphagia. *Dentomaxillofac Radiol 40*: 96-101, 2011.
- Syh HW, Chu WK, Kumar PP, Goede MR, Smith CL, Reeves MA and McCaul G.: Estimation of the mean effective organ doses for total body irradiation from Rando phantom measurements. *Med Dosim 17*: 103-6, 1992.
- Woo MK and Cunningham JR: The validity of the density scaling method in primary electron transport for photon and electron beams. *Med Phys 17*: 187-94, 1990.
- Ezzell GA, Burmeister JW, Dogan N, LoSasso TJ, Mechalakos JG, Mihailidis D, Molineu A, Palta JR, Ramsey CR, Salter BJ, Shi J, Xia P, Yue NJ and Xiao Y: IMRT commissioning: Multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119. *Med Phys 36*: 5359-5373, 2009.

Received January 21, 2013

Revised March 5, 2013

Accepted March 5, 2013